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MACHOs AND MOLECULAR CLOUDS IN GALACTIC HALOS[†]

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Abstract

Recent observations of microlensing events in the Large Magellanic Cloud by the MACHO and EROS collaborations suggest that an important fraction of the galactic halo is in the form of Massive Astrophysical Compact Halo Objects (MACHOs) with mass $\sim 0.1M_{\odot}$. We outline a scenario in which dark clusters of MACHOs and molecular clouds form in the halo at galactocentric distances larger than $\sim 10 - 20$ kpc, provided baryons are a major constituent of the halo. Possible signatures of the presence of molecular clouds in our galaxy are discussed. We also discuss how molecular clouds as well as MACHOs can be observed directly in the nearby M31 galaxy.

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1 Introduction

A fundamental question in astrophysics concerns the nature of the dark matter in galactic halos. While various exotic dark matter candidates have been proposed, present limits coming from primordial nucleosynthesis still allow a halo made of ordinary baryonic matter. A viable candidate are MACHOs which can be detected via the gravitational lens effect. Assuming a standard spherical halo model, Alcock et al. [1] have found that MACHOs contribute with a fraction $0.19^{+0.16}_{-0.10}$ to the halo dark matter, whereas their average mass turns out to be $\sim 0.08 M_{\odot}$. Thus, the problem arises how to explain the nature of the remaining amount of dark matter in galactic halos. We proposed a scenario [2] for the formation of dark clusters of MACHOs and molecular clouds in the galactic halo, which can be summarized as follows.

After its initial collapse, the proto galaxy (PG) is expected to be shock heated to its virial temperature $\sim 10^6$ K. Since overdense regions cool more rapidly than average (by hydrogen recombination), proto globular cluster (PGC) clouds form in pressure equilibrium with diffuse gas. At this stage, the PGC cloud temperature is $\sim 10^4$ K, its mass and size are $\sim 10^6 (R/kpc)^{1/2} M_{\odot}$ and $\sim 10 (R/kpc)^{1/2}$ pc, respectively. The subsequent evolution of the PGC clouds will be different in the inner and outer part of the galaxy, depending on the decreasing collision rate and ultraviolet (UV) fluxes as the galactocentric distance increases. Below 10^4 K, the main coolants are H_2 molecules and any heavy element produced in a first chaotic galactic phase. In the central region of the galaxy an Active Galactic Nucleus and/or a first population of massive stars are expected to exist, which act as strong sources of UV radiation that dissociates the H_2 molecules present in the inner part of the halo. As a consequence, cooling is heavily suppressed and so inner PGC clouds remain for a long time at temperature $\sim 10^4$ K, resulting in the imprinting of a characteristic mass $\sim 10^6 M_{\odot}$. Later on, the cloud temperature suddenly drops below 10^4 K and the subsequent evolution leads to the formation of stars and ultimately to stellar globular clusters. In the outer regions of the halo the UV-flux is suppressed, so that no substantial H_2 depletion actually happens. This fact has three distinct implications: (i) no imprinting of a characteristic PGC cloud mass shows up, (ii) the Jeans mass can now be lower than $10^{-1} M_{\odot}$, (iii) the cooling time is much shorter than the collision time. PGC clouds subsequently fragment into smaller clouds that remain optically thin until the minimum value of the Jeans mass is attained, thus

leading to MACHO formation in dark clusters. Moreover, because the conversion efficiency of the constituent gas in MACHOs could scarcely have been 100%, we expect the remaining fraction f of the gas to form self-gravitating molecular clouds, since, in the absence of strong stellar winds, the surviving gas remains bound in the dark cluster, but not in diffuse form as in this case the gas would be observable in the radio band.

2 Observational Tests

Let us now address the possible signatures of the above scenario, in addition to the single MACHO detection via microlensing.

We proceed to estimate the γ -ray flux produced in molecular clouds through the interaction with high-energy cosmic-ray protons. Cosmic rays scatter on protons in the molecules producing π^0 's, which subsequently decay into γ 's. An essential ingredient is the knowledge of the cosmic ray flux in the halo. Unfortunately, this quantity is experimentally unknown and the only available information comes from theoretical estimates. More precisely, from the mass-loss rate of a typical galaxy we infer a total cosmic ray flux in the halo $F \simeq 1.1 \times 10^{-4} \text{ erg cm}^{-2} \text{ s}^{-1}$. We also need the energy distribution of the cosmic rays, for which we assume the same energy dependence as measured on the Earth. We then scale the overall density in such a way that the integrated energy flux agrees with the above value. Moreover, we assume that the cosmic ray density scales as R^{-2} for large galactocentric distance R . Accordingly, we obtain [2]

$$\Phi_{CR}(E, R) \simeq 1.9 \times 10^{-3} \Phi_{CR}^{\oplus}(E) \frac{a^2 + R_{GC}^2}{a^2 + R^2} , \quad (1)$$

where $\Phi_{CR}^{\oplus}(E)$ is the measured primary cosmic ray flux on the Earth, $a \sim 5$ kpc is the halo core radius and $R_{GC} \sim 8.5$ kpc is our distance from the galactic center. The source function $q_{\gamma}(r)$, which gives the photon number density at distance r from the Earth, is

$$q_{\gamma}(r) = \frac{4\pi}{m_p} \rho_{H_2}(r) \int dE_p \Phi_{CR}(E_p, R(r)) \sigma_{in}(p_{lab}) < n_{\gamma}(E_p) > . \quad (2)$$

Actually, the cosmic ray protons in the halo which originate from the galactic disk are mainly directed outwards. This circumstance implies that the induced photons will predominantly leave the galaxy. However, the presence of

magnetic fields in the halo might give rise to a temporary confinement of the cosmic ray protons similarly to what happens in the disk. In addition, there could also be sources of cosmic ray protons located in the halo itself, as for instance isolated or binary pulsars in globular clusters. As we are unable to give a quantitative estimate of the above effects, we take them into account by introducing an efficiency factor ϵ , which could be rather small. In this way, the γ -ray photon flux reaching the Earth is obtained by multiplying $q_\gamma(r)$ by $\epsilon/4\pi r^2$ and integrating the resulting quantity over the cloud volume along the line of sight.

The best chance to detect the γ -rays in question is provided by observations at high galactic latitude. Therefore we find

$$\Phi_\gamma(90^\circ) \simeq \epsilon f \, 3.5 \times 10^{-6} \frac{\text{photons}}{\text{cm}^2 \text{ s sr}} . \quad (3)$$

The inferred upper bound for γ -rays in the 0.8 - 6 GeV range at high galactic latitude is 3×10^{-7} photons $\text{cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1}$ [3]. Hence, we see from eq. (3) that the presence of halo molecular clouds does not lead nowadays to any contradiction with such an upper limit, provided $\epsilon f < 10^{-1}$.

Molecular clouds can be detected via the anisotropy they would introduce in the Cosmic Background Radiation (CBR), even if the ratio of the temperature excess of the clouds to the CBR temperature is less than $\sim 10^{-3}$. Consider molecular clouds in M31. Because we expect they have typical rotational speeds of $50 - 100 \text{ km s}^{-1}$, the Doppler shift effect will show up as an anisotropy in the CBR. The corresponding anisotropy is then [4]

$$\frac{\Delta T}{T_r} = \pm \frac{v}{c} S f \tau_\nu , \quad (4)$$

where S is the spatial filling factor and T_r is the CBR temperature. If the clouds are optically thick only at some frequencies, one can use the average optical depth over the frequency range of the detector $\bar{\tau}$. We estimate the expected CBR anisotropy between two fields of view (on opposite sides of M31) separated by $\sim 4^\circ$ and with angular resolution of $\sim 1^\circ$. Supposing that the halo of M31 consists of $\sim 10^6$ dark clusters and that all of them lie between 25 kpc and 35 kpc, we would be able to detect $10^3 - 10^4$ dark clusters per degree square. Scanning an annulus of 1° width and internal angular diameter 4° , centered at M31, in 180 steps of 1° , we would find anisotropies of $\sim 2 \times 10^{-5} f \bar{\tau}$ in $\Delta T/T_r$ (as now $S = 1/25$). In conclusion,

the theory does not permit to establish whether the expected anisotropy lies above or below current detectability ($\sim 10^{-6}$), and so only observations can resolve this issue.

Let us now turn to the possibility of detecting MACHOs in M31 via their infrared emission. For simplicity, we assume all MACHOs have equal mass $\sim 0.08 M_{\odot}$ (which is the upper mass limit for brown dwarfs) and make up the fraction $(1 - f)$ of the dark matter in M31. In addition, we suppose that all MACHOs have the same age $t \sim 10^{10}$ yr [5]. As a consequence, MACHOs emit most of their radiation at the wavelength $\lambda_{max} \sim 2.6 \mu m$. The infrared surface brightness $I_{\nu}(b)$ of the M31 dark halo as a function of the projected separation b (impact parameter) is given by

$$I_{\nu}(b) \sim 5 \times 10^5 \frac{x^3}{e^x - 1} \frac{a^2(1 - f)}{D\sqrt{a^2 + b^2}} \arctan \sqrt{\frac{L^2 - b^2}{a^2 + b^2}} \text{ Jy sr}^{-1}, \quad (5)$$

where the M31 dark halo radius is taken to be $L \sim 50$ kpc. Some numerical values of $I_{\nu_{max}}(b)$ with $b = 20$ and 40 kpc are $\sim 1.6 \times 10^3 (1 - f) \text{ Jy sr}^{-1}$ and $\sim 0.4 \times 10^3 (1 - f) \text{ Jy sr}^{-1}$, respectively. The planned SIRTf Satellite contains an array camera with expected sensitivity of $\sim 1.7 \times 10^3 \text{ Jy sr}^{-1}$ per spatial resolution element in the wavelength range 2-6 μm . Therefore, the MACHOs in the halo of M31 can, hopefully, be detected in the near future.

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